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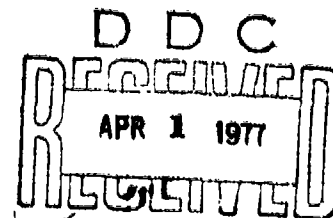
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DEVELOPMENT OF A 1093°C (2000°F) PROTOTYPE ACCELEROMETER

KAMAN SCIENCES CORPORATION ✓
1500 GARDEN OF THE GODS ROAD
COLORADO SPRINGS, COLORADO 80907

OCTOBER 1976

TECHNICAL REPORT AFFDL-TR-76-61
FINAL REPORT FOR PERIOD DECEMBER 1974 - APRIL 1976




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Also included are a description of the analytical and experimental investigations, the design of the sensor and electronics, the testing, the conclusions and recommendations.

Accomplishments of the research program included (1) the extension of the high temperature materials technology from the 1093°C (2000°F) acoustic microphone development to the design of a prototype accelerometer, (2) the advancement of high temperature transducer materials technology to include the use of refractory metals, (3) the design and fabrication of a sensor using variable capacitance as the acceleration sensitive measurand and (4) the design and fabrication of a frequency modulated (FM) electronic detection system utilizing the large signal-to-noise ratio of state-of-the-art FM components.

The resulting accelerometer system was tested for approximately 40 hours with 12 hours at temperatures above 1010°C (1850°F). After this period of time, the sensor failed to operate and a failure analysis pointed out two correctable design deficiencies. The performance of the system would be characterized as follows:

Operating Temperature Range: RT to 1093°C (RT to 2000°F)

Frequency Response: Flat to 3 kHz

Dynamic Range: 1000 to 0.03 g (91 dB)

Sensitivity Shifts: $\pm 10\%$ Ambient to 871°C (1600°F)

Linearity: $\pm 20\%$ Ambient to 871°C (1600°F)

Size: 12.3 cm³ (.74 in.³)

The recommendation to continue the development to allow for slight design changes and performance optimization was made by the authors.

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FOREWORD

The research described in this report was performed by Kaman Sciences Corporation, Colorado Springs, Colorado, under Air Force Contract F33615-74-C-3027, Project 1472, "Dynamics Measuring and Analysis Technology for Military Vehicles," and Task No. 147201, "Dynamic Testing Procedures of Flight Vehicles," for the Dynamics Technology Applications Branch, Structures Division, Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

The work was administered by Mr. Donald E. Seely, (AFFDL/FBG), Project Engineer, of the Structures Division.

John C. Schneider was the Program Manager and Richard K. Duke was the Project Engineer. Other members of the investigative team were Stan Bowlin, Bruce DuVall, Frank Hassey, Jim Lunghofer, and Art Witte.

This report covers work conducted from December 1974 to April 1976. This report was submitted by the authors on 6 May 1976.

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SECTION I

INTRODUCTION

This final report covers effort expended on Contract F33615-75-C-3027 with the Air Force Flight Dynamics Laboratory/FBG, Air Force Systems Command at Wright-Patterson AFB. Efforts of the program were directed at extending and advancing the high temperature acoustic microphone technology developed under Contracts F33615-72-C-1199 and F33615-74-C-3011 to the development of a prototype high temperature accelerometer. Such advancements are required to keep pace with the severe environments encountered in current aerospace programs.

Accomplishments of the research program included (1) the extension of the high temperature materials technology from the 1093°C (2000°F) acoustic microphone development to the design of a prototype accelerometer, (2) the advancement of high temperature transducer materials technology to include the use of refractory metals, (3) the design and fabrication of a sensor using variable capacitance as the acceleration sensitive measurand and (4) the design and fabrication of a frequency modulated (FM) electronic detection system utilizing the large signal-to-noise ratio of state-of-the-art FM components.

Included in this report are the objectives and goals of the development program, the details of the research effort, the design and fabrication details and the testing, including a comparison to the actual design goals. Also included are conclusions to the research program and recommendations for future efforts.

SECTION II

PROGRAM OBJECTIVES AND GOALS

The main objective of the development effort was to extend, and if possible, advance the current 1093°C (2000°F) technology to the design and fabrication of a high temperature accelerometer system. Additional objectives were to define the accelerometer system performance, obtain service life characteristics and to establish production techniques and procedures. The priorities, for purposes of design tradeoffs, were designated as the first four design goals listed for the program. These goals are listed in the order of importance, starting with operation temperature range of -54 to 1093°C.

The program design goals were as follows:

1. Operating temperature range: -54 to 1093°C (-65°F to 2000°F).
2. Frequency response: 2 to 20,000 Hz (DC to 20,000 Hz is desired).
3. Dynamic range: 100 dB (.01g to 1000g).
4. Sensitivity: vary no more than $\pm 5\%$ over given temperature range.
5. Linearity: within $\pm 1\%$ over the entire dynamic range.
6. Resonant frequency: 32,000 Hz or above.
7. Cross axis sensitivity: less than 1%.
8. Acoustic noise sensitivity: less than .01g equivalent at 140 dB SPL, (Ref. to 2×10^{-4} Microbar).
9. Static stability: .1% at a given temperature over an extended time period.
10. Dynamic stability: less than 10 dB shift above noise floor from temperature transients of up to 2.8°C/sec (5°F/sec) over the given temperature range.
11. Size: 12.29 cm³ (0.75 in³) or less.
12. External electronics: if required shall be simple, low power, compact, and flight qualified.

SECTION III
DEVELOPMENT PROGRAM SUMMARY

To meet the objectives and goals of the research effort, a detailed plan of activities was originated. The phases and tasks of the program plan were as follows:

PHASE I Technology Evaluation

1. Program Schedule
2. Literature Survey
3. Consultation with Experts
4. Sensing Technique Evaluations
5. Material Evaluations

PHASE II Preliminary Laboratory Tests and Design

1. High Temperature Materials
2. Assembly Methods
3. Promising Sensing Method Tests
4. Parameter Optimization Tests
5. Preliminary Accelerometer Design
6. Interim Report

PHASE III Breadboard Accelerometer Construction and Testing

1. Fabrication of Approved Accelerometer
2. Testing of Accelerometer

PHASE IV Final Accelerometer System Design

1. Incorporation of Minor Changes
2. Second Interim Report

PHASE V Prototype Accelerometer Construction and Testing

1. Construction of Approved Accelerometer Design
2. Testing of Accelerometer
3. Delivery of Accelerometer

PHASE VI Final Report

1. Draft of Final Report
2. Briefing at AFFDL
3. Final Report
4. Abstract of New Technology

Later, because of technical problems encountered in the development of the accelerometer, Phases III and IV were eliminated from the program. These tasks were eliminated to keep the program within the original funding limits without seriously compromising the overall quality of the development effort.

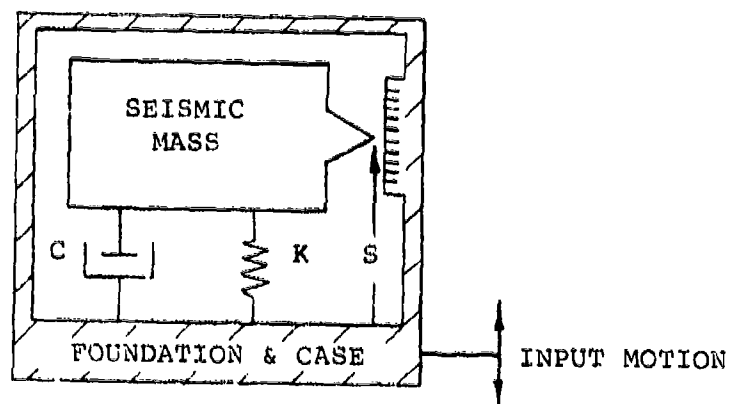
SECTION IV

ANALYTICAL EVALUATIONS

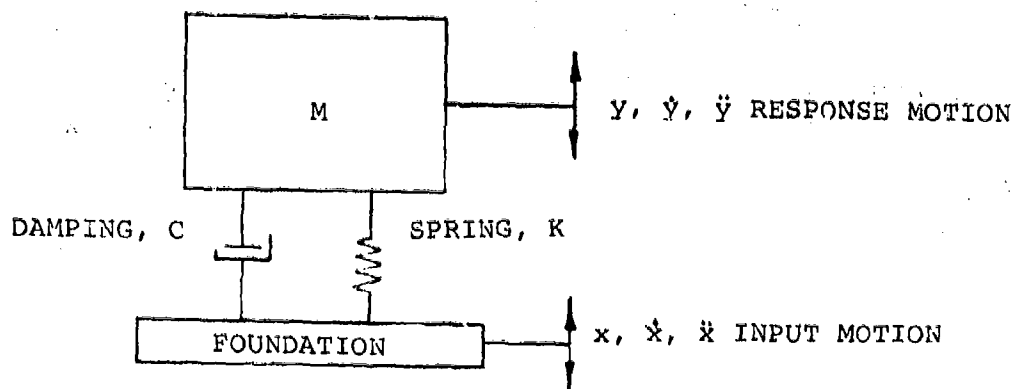
Following an extensive literature search, no new techniques were noted that could be used at 1093°C (2000°F) except those originally proposed. They were (1) optical, (2) eddy current, and (3) capacitance techniques. Noted in the optical techniques study were several systems used primarily for the measurement of either velocity or displacement. The most promising system noted was a laser velocity interferometer. While such a system would have the advantage of remote location which would allow its use to even greater temperatures than 1093°C, it has many disadvantages. These are (1) it does not measure acceleration directly, (2) it needs visual access (window) to test surface, (3) it is sensitive to thermal gradients which cause index of refraction changes, (4) vibration isolation of sensor with respect to test surface is required, and (5) present packaging requirements are considered extremely bulky and not suitable for airborne use.

1. SEISMIC SYSTEM ANALYSIS

With the optical techniques considered somewhat beyond the scope of this development program, most of the analytical effort was directed to the analysis of either an eddy current or capacitive type sensor. With either of these systems, the most important problem is the design of the seismic system as shown in Figure 1a. Such a system basically consists of four parts: 1) an integrated foundation and case, 2) a mass element, 3) an interconnecting spring which possesses material damping, and 4) a relative displacement detection device. Additional damping may be introduced using a fluid or gas damping device. Thus the accelerometer



A. SEISMIC ACCELEROMETER



B. ACCELEROMETER MODEL

FIGURE 1. SEISMIC ACCELEROMETER SCHEMATIC

can be modeled as a lumped system (Figure 1b) consisting of a foundation and a mass element interconnected with spring and damping elements.

a. Dynamic Analysis

For the following discussion, the displacement of the foundation and seismic mass with respect to a fixed coordinates system will be designated x and y respectively. The relative displacement will be designated by

$$\delta = y - x.$$

Consider the transducer subjected to an input motion x, \dot{x}, \ddot{x} . The displacement of the seismic mass with respect to a fixed point in space can be defined by $y = \delta + x$. The differential equation of motion for the system can be written as the familiar

$$m \frac{d^2(\delta+x)}{dt^2} + c \frac{d\delta}{dt} + k\delta = 0 \quad (1)$$

where

m = seismic mass

c = the damping co-efficient and

k = the spring constant.

Equation 1 can be written as

$$m \frac{d^2\delta}{dt^2} + c \frac{d\delta}{dt} + k\delta = -m \frac{d^2x}{dt^2} \quad (2)$$

Assuming that the motion $x = X_0 \cos \omega t$ and $\delta = \Delta_0 \cos \omega t + \theta$, the solution of Equation 2 can be put into the form

$$\frac{\Delta_0}{\ddot{X}_0} = \frac{1}{\omega_n^2} \left[\frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}} \right] \quad (3a)$$

and

$$\theta = \tan^{-1} \left[\frac{2\zeta \frac{\omega}{\omega_n}}{1 - \frac{\omega^2}{\omega_n^2}} \right] \quad (3b)$$

where

- Δ_o = displacement amplitude of mass element relative to the displacement of the foundation
- \ddot{x}_o = acceleration amplitude of the foundation
- ω = circular excitation frequency, ($\omega = 2\pi f$ where f is expressed in Hz)
- ω_n = undamped natural circular frequency of the spring mass system ($\omega_n = 2\pi f_n$ where f_n is expressed in Hz)
- ζ = damping expressed as a fraction of critical damping,

$$\frac{c}{2\sqrt{km}}$$

- θ = phase angle in degrees that the relative displacement of the mass element lags the acceleration foundation

Equation 3 is an expression for the magnitude and phase of the relative displacement of the seismic system. Notice that the magnitude of the relative displacement (or the sensitivity) is inversely proportional to ω_n^2 and directly proportional to a dimensionless quantity which will be designated as the frequency dependent sensitivity multiplier $M(\omega)$:

$$\frac{\Delta_o}{\ddot{x}_o} = \frac{1}{\omega_n^2} M(\omega)$$

where

$$M(\omega) = \frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}} \quad (4)$$

A plot of the sensitivity multiplier $M(\omega)$ is shown in Figure 2.

The expression $\frac{1}{\omega_n^2}$ is the static displacement sensitivity which can be written as

$$\left(\frac{\Delta_o}{g_o}\right)_{\text{static}} = \frac{980.6}{4\pi^2 f_n^2} \left[\frac{\text{centimeters}}{g} \right] \quad (5)$$

where

$$g_o = \text{one gravitational unit or } 980.6 \text{ centimeters/sec}^2 \text{ and}$$

$$f_n = \frac{\omega_n}{2\pi} \left[\text{Hz} \right]$$

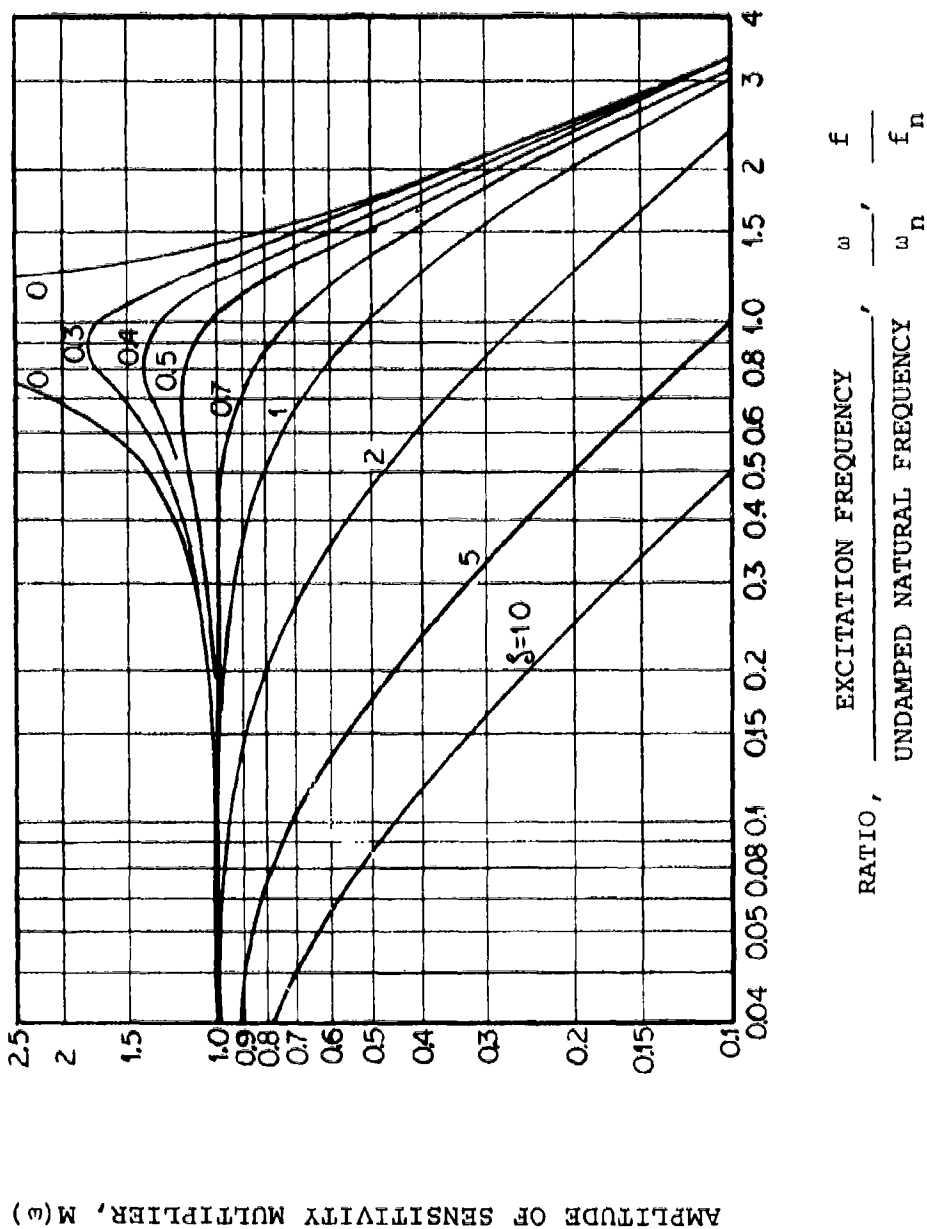


FIGURE 2. SENSITIVITY MULTIPLIER VS. FREQUENCY

The frequency dependent displacement sensitivity amplitude is equal to the product of the static sensitivity and the sensitivity multiplier,

$$\text{Sensitivity} = \frac{980.6}{4\pi^2 f_n^2} M(\omega) \text{ (centimeters/g)}$$

The phase of the sensitivity is expressed by Equation 3b and is plotted in Figure 3.

b. Accelerometer Operating Characteristics

An accelerometer to be useful must exhibit the following dynamic characteristics: 1) it must have a sensitivity amplitude which is invariant over the frequency range of interest and 2) it must have a phase which is linear over the same frequency range.

Considering the first characteristic, the useful frequency range of an accelerometer increases as its natural frequency increases. However, the relative displacement of the mass and foundation is inversely proportional to the square of the natural frequency; i.e., for a given X_0 or g_0 the relative displacement is proportional to $1/\omega_n^2$. Therefore, detection of small relative displacements is required for accelerometers having high natural frequencies or high frequency measurement capabilities. For an undamped accelerometer, the amplitude of the frequency response (sensitivity) is flat within 5% to approximately $.2\omega_n$ as shown in Figure 2. Thus the undamped accelerometer can be used to measure frequencies to at least 20% of the accelerometer natural frequency without excessive distortion of the waveform amplitude.

As previously indicated, the sensitivity phase is also of importance in reproducing an undistorted waveform. If

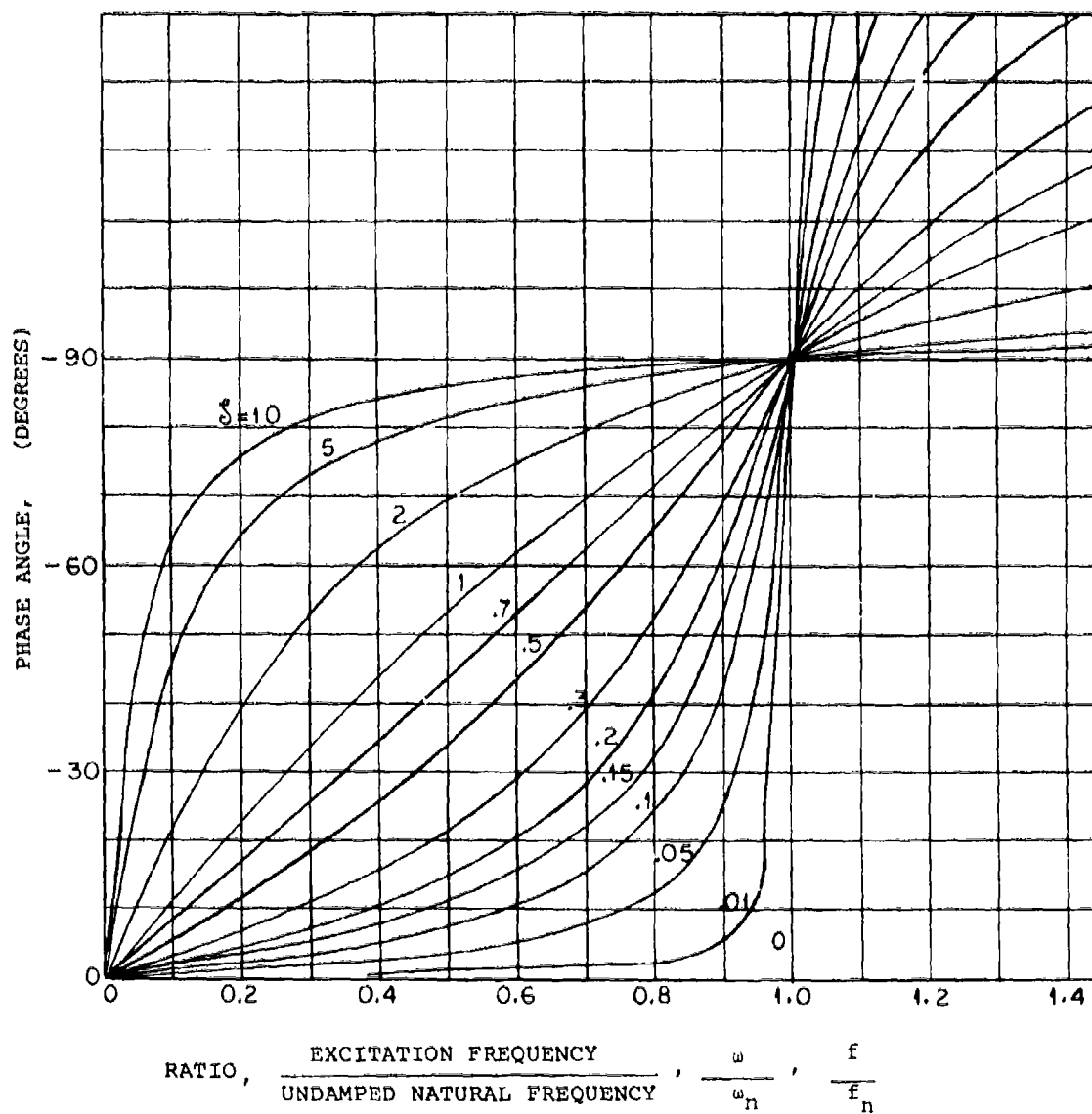


FIGURE 3. PHASE VS. FREQUENCY

the accelerometer is undamped, $\theta = 0$ for values of $\omega/\omega_n \leq 1$, then the phase of the response is equal to the phase of the useful range of the accelerometer. Thus considering both amplitude and phase characteristics, the undamped accelerometer reproduces an undistorted waveform to at least 20% of its undamped natural frequency.

Damping can be employed to extend the upper frequency range of an accelerometer; however, the effects of a phase shift may introduce unwanted distortion in the response of the accelerometer. Unless the phase characteristics meet the requirement of a linear shift with frequency, response distortion will be introduced. Referring to the phase plot shown in Figure 3, only two conditions result in a linear phase shift. The first is with zero damping. The implications of this condition have been previously discussed. This condition results in a linear phase shift with zero slope and a zero time delay between the input to the accelerometer and its response. The second condition occurs when the damping ratio $\zeta \approx .7$ and the phase angle θ increases linearly with frequency to approximately 1.2 times the accelerometer's natural frequency. Referring to the plot for $M(\omega)$ (Figure 2) it can be seen that the sensitivity amplitude is flat within 5% to 60% of ω_n . Thus the accelerometer will reproduce the input to a frequency of 60% of the transducer's natural frequency without amplitude or phase distortion. However, a time delay equivalent to the phase shift will result between the acceleration input to and the displacement response (electrical output) of the transducer.

c. Summary

The following briefly summarizes the effects of accelerometer dynamic characteristics on its operations characteristics.

- (1) The useful frequency range of an accelerometer is directly proportional to its undamped natural frequency.
- (2) The basic sensitivity is inversely proportional to the square of the accelerometer's undamped natural frequency. Therefore, accelerometers with high natural frequencies have low sensitivity characteristics and require more sensitive detection capabilities.
- (3) Compromises must therefore be made between high frequency measurement capabilities and high sensitivity characteristics.
- (4) Introduction of damping can increase the high frequency capabilities of an accelerometer.
- (5) Only two damping conditions exist which result in no distortion in the measurement of the input acceleration. These are
 - (a) when the accelerometer is undamped and
 - (b) when the damping is approximately 70% of critical damping.
- (6) The maximum frequency at which accelerations can be measured without distortion is
 - (a) approximately 20% of the accelerometer's undamped natural frequency for zero damping and
 - (b) approximately 60% of the accelerometer's undamped natural frequency for 70% critical damping.
- (7) Damping in an accelerometer introduces a time delay between input motion and accelerometer response.

2. DIAPHRAGM DESIGN

Applying these dynamic characteristics to the design of a seismic element, a diaphragm of outside radius $a = 1.27$ cm (0.50 in) and button radius $b = 0.97$ cm (0.38 in) was considered. The following dynamic characteristics would be predicted for a complex diaphragm shown in Figure 4. The natural frequencies correspond to seismic systems that would have useable frequency ranges for the undamped condition of 11, 6.4 and 2.7 kilohertz respectively.

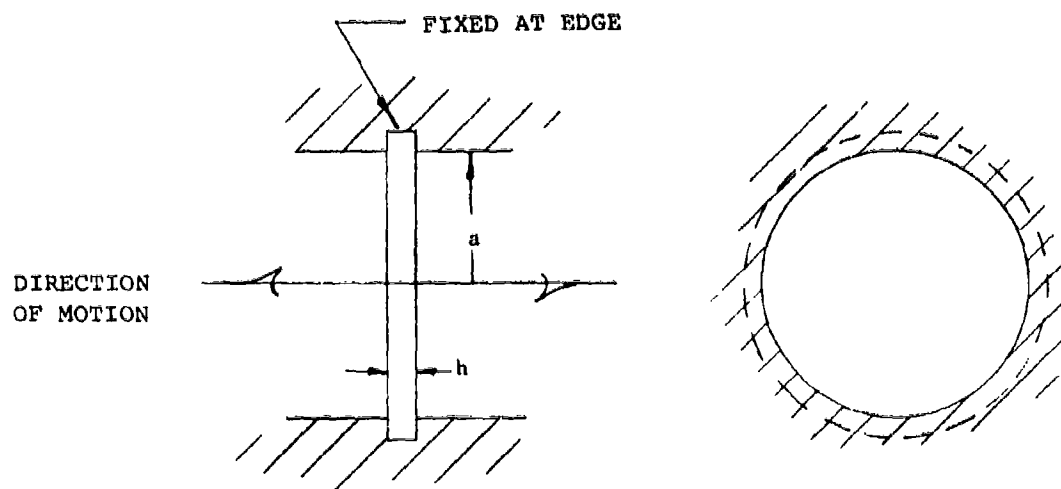
Natural Freq.	h_b	h	Displacement @ .01g	Displacement @ 1000g
(kHz)	(cm)	(cm)	(cm)	(cm)
55	.480	.120	82.17×10^{-12}	82.17×10^{-7}
32	.279	.070	242.80×10^{-12}	242.80×10^{-7}
13.5	.104	.026	1364.00×10^{-12}	1364.00×10^{-7}

The strong dependence of frequency response and dynamic range can be seen from this list since the dynamic range will be directly related to the actual displacement. Past experience with eddy-current systems suggests that only displacement values of 127×10^{-10} cm or greater can be detected via the eddy-current technique, but capacitance techniques should extend this detection capability.

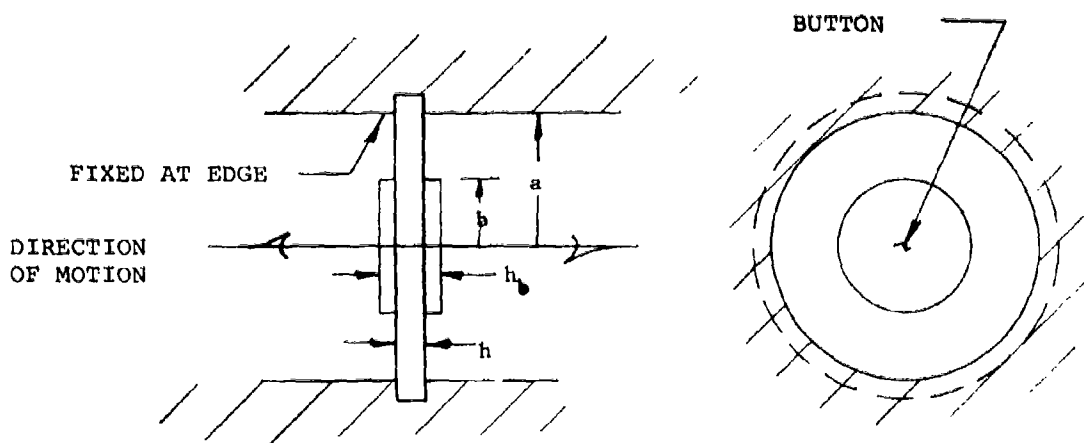
3. ELECTRONICS DESIGN

a. Capacitance Plate Characteristics

Table 1 shows the initial capacitance and capacitance changes due to acceleration for sensors with three different resonant frequencies and six different plate spacings. The sensitivity in picofarads/g of acceleration (pf/g) is also given for each geometry. There are two results that can be readily seen. First, smaller plate spacing results in a sensor with a larger static capacitance, greater capacitance



A. SIMPLE DIAPHRAGM



B. COMPLEX DIAPHRAGM

FIGURE 4. DIAPHRAGM GEOMETRY

TABLE 1. CAPACITANCE PLATE CHARACTERISTICS

Cap Plate Spacing	Initial Cap C(pf)	fn = 13.5 KiloHertz		fn = 33 KiloHertz		fn = 55 KiloHertz	
		Accel Sens C/G	Capacitance Change (pf)	Accel Sens C/G	Capacitance Change (pf)	Accel Sens C/G	Capacitance Change (pf)
d(cm)		(pf/G)	@100G's	(pf/G)	@0.01G's	(pf/G)	@0.01G's
.00254 (.0010 in)	104.1	5.58x10 ⁻³	5.58	0.93x10 ⁻³	0.93	0.34x10 ⁻³	.34
.00203 (.0008 in)	130.2	8.72x10 ⁻³	8.72	1.45x10 ⁻³	1.45	0.53x10 ⁻³	.53
.00152 (.0006 in)	173.6	15.5x10 ⁻³	15.5	2.59x10 ⁻³	2.59	0.93x10 ⁻³	.93
.00102 (.0004 in)	260.3	34.9x10 ⁻³	34.9	5.84x10 ⁻³	5.84	2.10x10 ⁻³	2.10
.00051 (.0002 in)	520.7	139.6x10 ⁻³	139.6	23.4x10 ⁻³	23.4	8.41x10 ⁻³	8.41
.00025 (.0001 in)	1041.0	558.3x10 ⁻³	558.3	93.4x10 ⁻³	93.4	33.6x10 ⁻³	33.6

changes and better sensitivity. All of these factors are desirable to obtain the best signal. Secondly, a sensor with a lower resonant frequency gives greater capacitance changes and therefore better sensitivity. This says to obtain the optimum signal, the sensor should have a very small plate spacing and a low resonant frequency.

b. Proposed Capacitance Sensor Electronics

The electronics used to detect the sensor capacitance change will consist of well-established circuits. As shown in the block diagram of Figure 5, the system consists of the sensor capacitor, an interconnecting cable, an oscillator, an FM detector, and a variable gain amplifier.

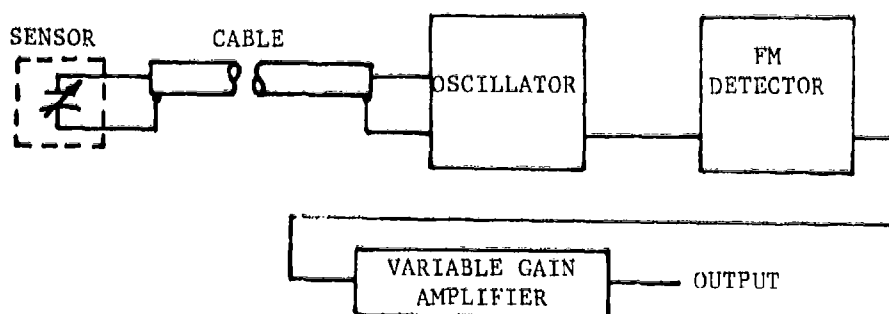


FIGURE 5. PROPOSED ELECTRONICS

The interconnecting cable will be, at least in part, a 1093°C (2000°F) cable. It is expected that this cable will be very lossy and therefore part of the cable may be a lower loss medium temperature cable.

The oscillator to be used could be any one of several well proven oscillators. The three most commonly found in the literature are the Hartley, Colpitts and Clapp oscillators.

All three oscillators have the frequency of oscillation given by the same equation and therefore would have the same intrinsic sensitivity to a small change in capacitance. The Colpitts oscillator was chosen for testing because it requires only a single coil to tune the oscillator. The simplified circuit is shown in Figure 6. The frequency of oscillation f_o is equal to $\frac{1}{2\pi\sqrt{LC}}$.

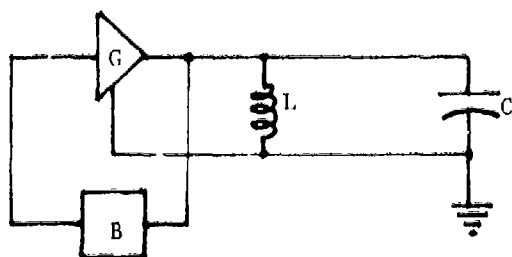


FIGURE 6. COLPITTS OSCILLATOR

The detector required to demodulate the FM signal will be a standard FM receiver. Of the various types of discriminators available, the phase locked loop (PLL) is a natural selection for this application. It has excellent noise suppression and is comparable to conventional discrimination techniques in other characteristics*. The PLL does have a limitation in the signal to noise ratio. The severity of this limitation needs to be determined. Phase locked loops are available in integrated circuit form as an off-the-shelf item.

* H.L. Van Trees, Detection, Estimation, and Modulation Theory, John Wiley and Sons, New York, 1971.

The variable gain amplifier is necessary to both amplify the small signal from the PLL and to correct for the change in sensitivity that will be caused by temperature shifts. The gain control for the amplifier will be derived from a d.c. resistance measurement of the cable.

There are two basic problems that must be overcome to provide an accurate measurement of acceleration over the desired temperature range. The first problem was mentioned above; the sensitivity varies with temperature. This is caused by at least two factors. First is the change in the sensor capacitor plate spacing due to thermal expansion. This problem is amplified with a smaller static spacing of the plates. The second cause is changing parameters of the cable due to temperature changes. The resistance of the conductors and the dielectric of the insulator both vary as a function of temperature. The second problem is a d.c. shift in output due to temperature changes. The causes are the same as before; spacing of the plates and the cable parameters change with temperature. The first problem can be solved, as stated above, by measuring the d.c. resistance and hence the average temperature of the cable and varying the gain of the final amplifier. A thermocouple in the sensor could also be used to determine the temperature. The second problem can be corrected by altering the f_o of the oscillator in a direction opposite that of thermal drift. However, the expansion of the plate spacing may be very large compared to the deflection caused by 0.01g. If this correction cannot be satisfactorily made, the system may have to be limited to a.c. response only.

c. Cable Characteristics

The capacitive sensor is connected to the oscillator circuit with a high temperature cable which is inescapably a source of inaccuracy and instability. The following analysis has used frequency, temperature and line length as variable parameters. The circuit analyzed is shown in Figure 7.

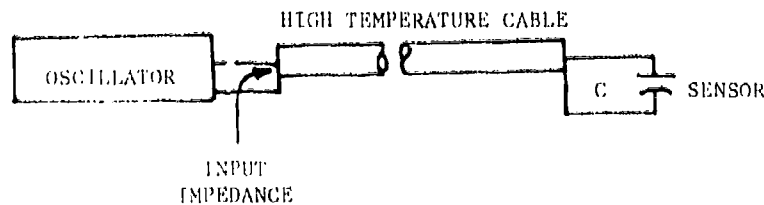


FIGURE 7. CABLE SCHEMATIC

A coaxial cable was selected for the analysis as being representative of nearly any cable which might be used. The expressions for characteristic impedance and propagation constant are readily analyzed; the results in the form of trends are applicable to any cable.

Using handbook values for the properties of the cable at room temperature and 1093°C, the characteristic impedance, propagation constant, input impedance and sensitivity values were studied as a function of temperature, frequency and geometry. The summary of these activities indicate that the interconnecting cable can significantly transform the transducer capacitance and reduce the sensitivity depending upon the length. Both a null shift and the reduction in sensitivity become more pronounced at higher frequencies. Longer lengths of cable, especially at higher frequencies, will make tuning the oscillator more difficult and place more serious demands upon the transducer and electronics design.

d. Eddy-Current Sensor Electronics Design

In the literature survey, many different bridge techniques were discussed, especially with many of the high accuracy capacitance systems. Although many of the systems had interesting features, none presented had identifiable characteristics that surpassed those achieved by the KP-1910 special electronics. These electronics were especially modified for the 1093°C (2000°F) microphone program* where a dynamic range in excess of 100 dB was achieved with excellent system temperature characteristics. From this evaluation, no work is planned with regard to bridge-type electronics. If needed, the KP-1910 Special electronics will be used for the breadboard electronics.

e. Eddy-Current Coil Design

The first two priorities in the list of design goals are the ability to withstand 1093°C (2000°F) operating temperatures and to have the transducer's frequency response range extend to 20,000 hertz. The materials used in the coil, both the wire and insulation, determine the maximum operating temperature. These considerations are discussed in detail in Section IV 4. The second goal, frequency response up to 20,000 hertz, necessarily implies that the displacements that the coils must detect are very, very small. (See Section IV 2.) Therefore the coils must be designed for maximum sensitivity as the prime consideration.

The basic principle of operation of Kaman's eddy-current devices is that a coil's impedance changes as a conductive target moves in a direction perpendicular to the axis of the coil.* An analytical solution for the eddy-current problem of a coil of rectangular cross-section above

*AFFDL-TR-73-62 Development of a 1093°C (2000°F) Prototype Microphone, February 1974.

a multi-layered plane can be performed. For some time now, Kaman has had computer programs available for use in transducer design. These programs include the solution of the eddy-current problem in conjunction with various subroutines that include different bridge circuits, non-linear pressure-displacement calculations, circuit variables, and the coil parameters.

The parameters that can be considered by the computer program for the coil design include the following: the coil dimensions (inner radius, outer radius and length), the coil wire size and resistivity, the target material and its resistivity and permeability, the coil-target geometry, the operating frequency, the connecting cable characteristics, and the circuit parameters of the different bridge circuits.

The computer program is not an optimization program per se. However, by varying the parameter of interest, it is possible to optimize with respect to that parameter. One cannot simply optimize one variable at a time because of the very complicated manner in which many of the variables interact and the rather complicated boundary conditions that exist. For example, one must consider such variables as how difficult it will be to wind a given coil uniformly from one coil to the next because the transducer must use matched coils. Additional details of such trade-offs are discussed in Section V 4.b. of this report.

The preliminary coil designs for the prototype eddy-current sensor have been completed. There are basically two different coils proposed. One operating at Kaman's usual operating frequency of 1 MHz with a somewhat larger than usual coil. The other coil operating at 5 MHz and having

only a single layer of wire windings. The second coil will have twice the sensitivity of the first but will require winding a coil in a different manner than our usual coil winding techniques.

4. MATERIALS EVALUATIONS

a. Materials Properties

In evaluating materials for the 1093°C accelerometer, two factors were kept in mind: 1) the materials experience of the 1093°C microphone development and 2) that an inherent high natural stiffness could reduce the size and weight of the sensor. Realizing that the number one priority was, of course, operation at 1093°C, the materials used on the microphone program were evaluated first. However, because of size considerations, the search was expanded to include all materials that could operate above 1093°C that would have inherent high stiffness. The final candidates, after the obviously unusable ones were eliminated, were as follows:

Columbium (Niobium)	Rhodium
Iridium	Tantalum
Molybdenum	Tungsten
Palladium	Vanadium
Platinum	Haynes Alloy 8077
	Inconel Alloy MA754

Of these materials, five had stiffness characteristics which were better than the main group. Ranked in order they are as follows:

<u>Material</u>	<u>Stiffness Factor @ 1093°C</u>
Molybdenum	92
Iridium	76
Rhodium	75
Inconel Alloy MA753	64
Haynes Alloy 8077	60

where the stiffness factor is related to the ratio of the

modulus of elasticity to the density. Thus for a given natural frequency, the thickness of a seismic diaphragm of molybdenum would be considerably less than that of Haynes Alloy 8077 (approximately 70%).

From an examination of the materials available, three alternatives were felt to exist:

System I (low risk)

- Case Material - Haynes Alloy 8077
- Deflection Element - Rhodium or Haynes 8077
- Lead Wires - ZGS Platinum
- Ceramic Cement - Cotronics 901
- Coil Wire (if required) - Secon "E" coated rhodium
- Ceramics - 99.9+% Alumina
- Backfill - Vented

System II (moderate risk)

- Case Material - Haynes Alloy 8077
- Deflection Element - TZM Molybdenum
- Lead Wires - ZGS Platinum or HT Molybdenum
- Ceramic Cement - Cotronics 901
- Coil Wire (if required) - Secon "E" coated Molybdenum
- Ceramics - 99.9+% Alumina
- Backfill - High Purity Neon

System III (high risk)

- Case Material - Silicide Coated Molybdenum
- Deflection Element - TZM Molybdenum
- Lead Wires - HT Molybdenum
- Ceramic Cements - Cotronics 901
- Coil Wire (if required) - Secon "E" coated Molybdenum
- Ceramics - 99.9+% Alumina
- Backfill - High Purity Neon

b. Chemical Compatability

A literature search was made to determine what potential problems might exist with the use of molybdenum alloy as the deflection element, a superalloy as the case material, aluminum oxide and Cotronics 901 cement for the coil assembly, and neon as a damping gas.

The selection of the TZM molybdenum alloy, because of its high recrystallization temperature and high strength for use at 1093°C, narrowed the compatability investigation by excluding molybdenum and HT molybdenum alloy as possible candidate materials.

The compatability of TZM and aluminum oxide (alumina) is well-known because of the use of both materials in high temperature (1650°C) furnaces. Alumina and TZM are non-reactive in an inert atmosphere up to 1370°C, and in a 10^{-4} torr vacuum up to 1650°C.

However, the use of Cotronics 901 cement may present some potential problems because of the silicon dioxide (silica) and carbon in the cement. Very little is known about whether silica can cause embrittlement by coming in contact with TZM at 1093°C, but carbon can react with molybdenum and its alloys at temperatures as low as 1200°C.

The second potential problem is the diffusion of nickel from the superalloy into the TZM thus causing embrittlement and failure. It is known that nickel and chromium vaporize in hard vacuums at 1200°C to form brittle intermetallic compounds, and may react in a like manner in an inert atmosphere.

The third potential problem is the embrittlement of TZM by very small quantities of oxygen. Oak Ridge National Laboratories has conducted tests demonstrating that as little as 300 ppm of oxygen can cause complete loss of ductility over the temperature range we expect to operate.

The use of neon gas will present no problems since inert gases have been used for sometime as atmospheres for molybdenum at elevated temperatures.

A summary of the potential problems are:

- (1) Reaction of the Cotronics 901 cement with the TZM alloy.
- (2) Nickel diffusion from a superalloy
- (3) Oxygen embrittlement.

5. PROCESS EVALUATION

a. Gas Damping

The most desirable situation with respect to damping of the accelerometer would be to have the accelerometer meet the design goals without any damping, the reason being that damping will introduce even more complexity into an already complex design. The technology evaluation performed to date has shown that it is unlikely that the systems considered, either capacitive or eddy-current, will have the combination of adequate frequency response and dynamic range.

The addition of a frequency dependent damping system can result in extending the frequency response up to and beyond the resonant frequency. In this manner, one can lower the resonant frequency of the accelerometer, thereby gaining sensitivity. This gain is not without its costs,

however. The costs include greater complexity, additional phase distortion and the damping is not expected to remain constant with temperature. The mathematical analysis of the frequency dependent damping system is quite involved - straightforward but tedious. To examine the temperature effects, it will be necessary to program the mathematics on a computer and have the computer search for optimum solutions. The effort is considered beyond the scope of this program, and a design with no gas damping was recommended.

b. Welding and Brazing

Of the materials selected for possible use, all have excellent welding and brazing properties. Kaman has extensive experience with all the materials except molybdenum and its alloys. Its joining properties are well-established in the literature since it has had extensive use in high temperature fixtures and ceramic-to-metal seals. Welding, brazing and spot-welding tests were implemented in the experimental phase.

c. Ceramic Cements

With the success of Cotronics 901 ceramic cement in the 1093°C microphone program, no new ceramic cement evaluations were planned. Compatibility tests of Cotronics 901 and the molybdenum configuration were also implemented.

SECTION V
EXPERIMENTAL EVALUATION

1. HIGH TEMPERATURE MATERIAL TESTS

Several compatability tests were conducted using Haynes Research Alloy #8077 as a test chamber. The first series of tests examined the question of nickel diffusion into the TZM molybdenum proposed as the seismic beam material. Such diffusion would cause embrittlement and premature failure. TZM molybdenum was tested in plain test capsules and capsules lined with a thin molybdenum sheet. The capsules were evacuated, backfilled with research grade neon and then heated at 1093°C (2000°F) for 100 hours. Photomicrographs of the tested TZM molybdenum are shown in Figures 8, 9 and 10. Conclusions to these tests indicated that the molybdenum had to be protected from the nickel diffusion since severe brittleness was noted in subsequent bend tests.

Since the molybdenum sheet was successful in protecting the TZM molybdenum, a vendor who could apply the molybdenum plating to the Haynes #8077 alloy was sought. The only vendor that could be found could not plate with molybdenum, but could apply tungsten plating. A test capsule was fabricated and forwarded for tungsten plating. Results of this test were successful, indicating no significant nickel diffusion after 100 hours at 1093°C.

After the remaining design features were established, a final total compatability test was conducted. However, in the interest of time and expense, a piece of nickel tubing lined with thin molybdenum was used as the test capsule. The test was disastrous. Strong indications of nickel embrittlement were noted on the TZM molybdenum and the

100X

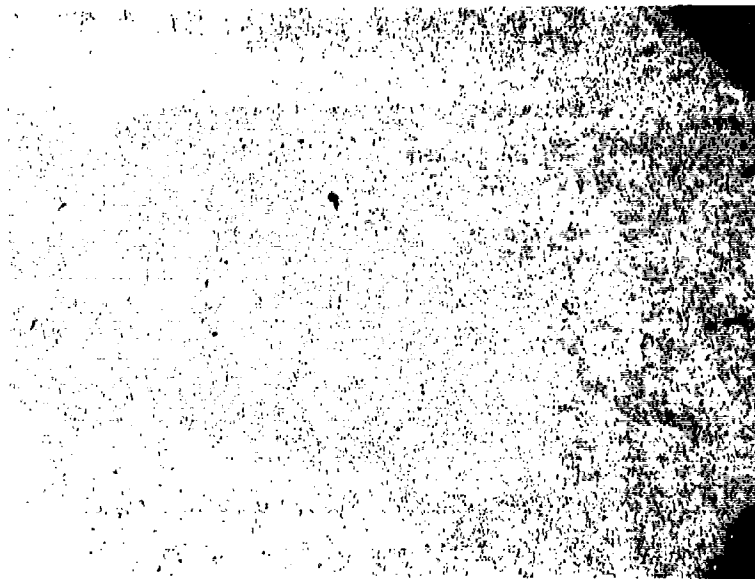


FIGURE 8. UNTESTED TZM MOLYBDENUM

100X



FIGURE 9. T2M MOLYBDENUM TESTED FOR 100 HRS
@ 1093°C IN MOLYBDENUM LINED NICKEL CAPSULE

100X



FIGURE 10. TZM MOLYBDENUM TESTED FOR 100 HRS
@ 1093°C IN UNLINED NICKEL CAPSULE

platinum plating lifted from the ceramic plate used on the other side of the capacitance plate. A close review of the results indicated that the 100% nickel container was not indicative of the results that would be obtained with the 80% nickel - 16% chrome system of the Haynes 8077 alloy. The test was then repeated in a Haynes 8077 alloy test capsule providing total confidence that the materials system could survive the 1093°C environment for a least 100 hours.

2. ASSEMBLY METHODS

b. Joining Tests

Since vast experience has already been gained with joining of all of the materials proposed on the 1093°C accelerometer program except molybdenum, spot welding, LASER welding, TIG welding and vacuum brazing tests were performed with TZM molybdenum.* As was anticipated from the analytical study, most joining techniques were highly successful as indicated by the following list:

<u>Joining Technique</u>	<u>Results</u>
Spot Welding	Strong joints with no difficulty.
LASER Welding	Requires special High Voltage setting. Some cracks in welds.
TIG Welding	Large fusion welds with no problems.
Brazing	Vacuum furnace power capability initially too low to test. Power capability increased and successful brazes made.

* TZM molybdenum samples were supplied by Schwarzkopf Development Corporation and AMAX Specialty Metals Division.

b. Ceramic Plating and Brazing

The design of the fixed portion of the capacitance plate consisted of a ceramic (alumina) plate, plated with a flash of platinum and electrodeposited rhodium with a ZGS platinum* center electrode brazed to the rhodium surface.

Evaluation of the plating and brazing processes were extensive. Many difficulties were encountered and experts in the field of ceramic-to-metal bonding were consulted. The major problems and their solutions were as follows:

<u>Problem</u>	<u>Solution</u>
(1) Flatness of the ceramic plate after machining.	(1) Ceramic plates were diamond lapped after rough machining.
(2) Brazing of electrode to rhodium plating caused cracking of the ceramic plate.	(2) Kaman's vacuum furnace was found to be totally inadequate. A high temperature vacuum furnace at the Colorado School of Mines was used to provide a uniform temperature brazing environment.
(3) Flatness of the ceramic plate after brazing.	(3) Since the plating was less than 0.001 inches thick, final diamond lapping could not remove more than 0.0005 inches of the plating. It was found that the ceramic plates had to be placed on an extremely flat substrate during the brazing process to assure a final acceptable flatness.

*Trademark of the Mattney-Bishop, Inc.

3. PROMISING SENSING METHOD TEST

a. Experimental Cable Characteristics

From the theoretical analysis, two qualitative assumptions could be predicted; an increase in frequency and an increase in temperature would both increase losses. Experiments with the high temperature cable and the Colpitts oscillator showed these assumptions to be true. Two experiments were performed on the cable to determine its characteristics versus temperature and frequency.

The first experiment measured the capacitance, inductance, resistance and shunt conductance of a 15.24 cm (6 in) piece of cable. This length was chosen because it could be uniformly heated in the oven. A Hewlett-Packard Model 4721A 1MHz digital LCR meter was used to measure the parameters. At this frequency the wave length is very much greater than the cable length. Therefore, the lumped circuit values could be measured. Measurements were made between the conductor and the sheath.

The measured capacitance data indicated capacitance increases of 31% from room temperature to 1093°C. This is caused primarily by a dielectric constant increase with temperature. The shunt conductance for the same cable indicated that the conductance increases by almost two orders of magnitude. The inductance of the piece of test cable remained within 1% of its value of 0.81 μ h over the temperature range. The conductor resistance increased by almost a factor of two from room temperature to 1093°C.

The second experiment used a longer piece of cable with only a portion of the cable heated similar to what a production unit would be subject to. The setup is shown in Figure 11.

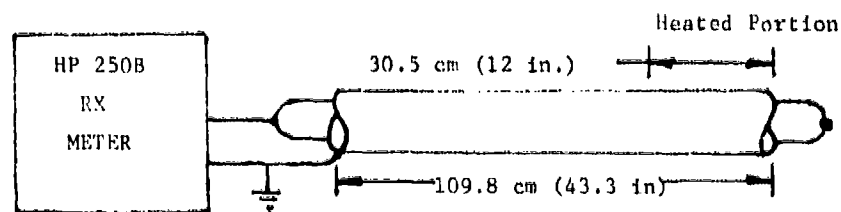


FIGURE 11. CABLE TEST

In this experiment both conductors were shorted together and measurements were made between this shorted pair and the sheath. The RX meter was used because the test frequency is selectable. Measurements were taken at 2 and 4 MHz. Measurements taken at higher frequencies were inconsistent. The interesting data from this experiment indicated that the conductance through the Al_2O_3 insulation increased with temperature and also with frequency.

b. Experimental Electronics Characteristics

The detailed schematic of the Colpitts oscillator is shown in Figure 12.

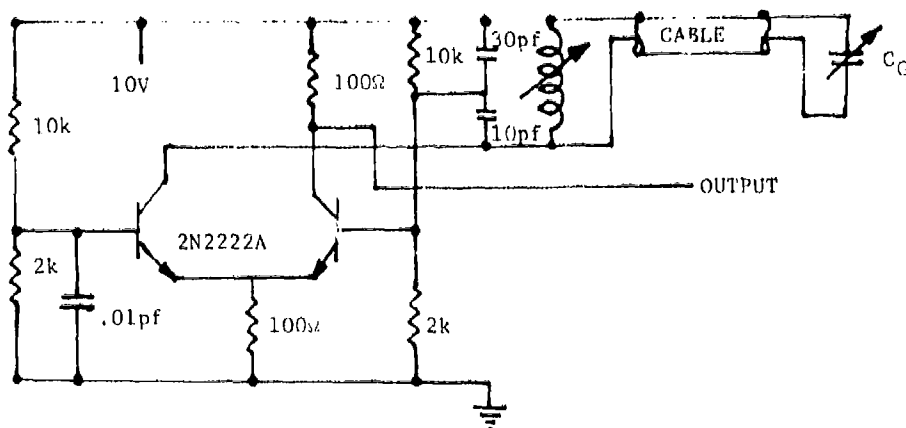


FIGURE 12. COLPITTS OSCILLATOR SCHEMATIC

The oscillator and capacitor with no cable was placed inside an ambient temperature enclosure to reduce temperature variations and its frequency was observed. The nominal frequency was 10.33 MHz. The frequency was monitored with a frequency counter; therefore, only low frequency deviations were observed. The average short term (1 second) deviation was about 50 Hz. Often this deviation was as low as 10 Hz. Over a period of six hours the frequency decreased by 300 Hz. For this test the oscillator had not been thermally compensated although the differential amplifier makes the circuit inherently stable.

The oscillator was very sensitive to stray capacitances to ground. Touching leads or cables could cause a several hundred Hz deviation in frequency. It was also moderately sensitive to power supply variations even with decoupling of the supply.

4. PARAMETER OPTIMIZATION STUDIES

a. Electronics and Cable Limitations

Through experimentation and testing performed on the oscillator and high temperature cable, several limitations were observed. The first limitations to be noted here apply to both the variable capacitive system and eddy-current system. Following this will be limitations dealing with each system individually.

A primary limitation of any system that is to operate at 1093°C is the interconnecting cable. To withstand this temperature extreme, materials must be chosen which result in a cable with significant losses. The conductance varied

from a satisfactory value at room temperature to a very lossy value (9×10^{-5} mhos at 1 MHz) at 1093°C. The static and low frequency capacitance also varied substantially with temperature. The transducer capacitance and the variable inductance make up the tank circuit and determine the frequency of oscillation. If the length of the cable is less than 1/4 of a wave length, the inductor is used to tune the oscillator. If the cable length is between 1/4 to 1/2 a wave length, the coil is replaced by a capacitance. An RF choke is also necessary for bias. This change is necessary because the input impedance of the cable becomes inductive. For longer lengths the cable looks alternately capacitive and then inductive.

A 244 cm (96 in) piece of Micro-dot cable with a geometry and characteristic impedance similar to the high temperature cable was connected to the oscillator. A 480 pf capacitor was used to simulate the transducer capacitor. Either a coil or a capacitor was used to tune the oscillator to frequencies between 2 and 17 MHz. The change $\Delta f_o/f_o$ for a 1% change in transducer capacitance for the various frequencies was measured. In this range of frequencies, it was observed that the sensitivity decreased with frequency increases. The theoretically ideal sensitivity of 0.5 was not met. It should be noted here that the oscillator and capacitor together with no cable achieved a sensitivity factor of 0.488.

Another experiment was performed where the frequency of oscillation was held close to 7.5 MHz and the length of the cable was varied. The length was varied from 30 to 244 centimeters. For lengths of cable between 30 and 122 cm, the sensitivity remained very close to 0.45. At these lengths an inductor was used in the oscillator to tune the

desired frequency. For lengths 305 cm and greater, a capacitor was used to tune the oscillator. At these lengths the sensitivity dropped to about 0.22. The oscillator could not be made to oscillate at 7.5 MHz with a 244 cm cable. These results indicate that the cable should be as short as possible to minimize losses and undesired shunt capacitance.

It was shown earlier that the sensitivity of the transducer is proportional to one over the square of the resonant frequency of the deflection element. This is true of any type of sensing technique. Preliminary laboratory tests with the variable resonance system give an indication of the performance with various resonant frequencies and capacitor plate spacings. Using the values of capacitance and capacitance change per g from Table 1 and a suitable $\Delta f_o / \Delta C$ value of 0.3 from the testing described earlier, dynamic range values were calculated for each configuration. These values are listed in db in Table 2. It should be emphasized that the absolute magnitude of these values may not be accurate, but their relative values are important. It can be seen that very significant gains can be made by both lowering the transducer resonant frequency and decreasing the plate spacing.

It is possible to reduce both amplitude and phase noise by controlling the thermal environment of the electronics. Therefore, to increase the values shown in Table 2, it probably will be necessary to have the critical electronics placed in an oven.

Design goal number 2 is a frequency response of 2 to 20,000 Hz or if possible from dc to 20,000 Hz. There is, in theory, no reason why dc response is not possible. However,

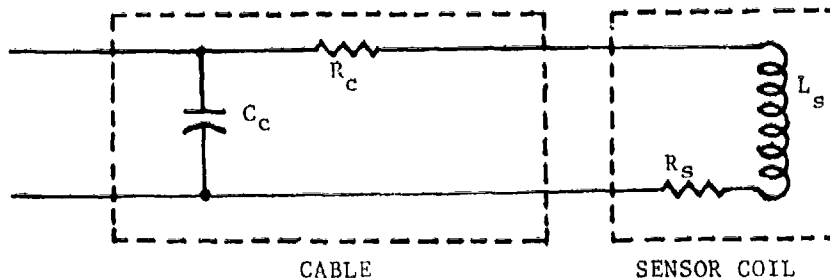
TABLE 2. SIGNAL TO NOISE RATIO IN DB

CAPACITANCE PLATE SPACING d (cm)	$f_n = 13.5$ KHz	$f_n = 33$ KHz	$f_n = 55$ KHz
.0025 (.0010 in)	64	49	40
.0020 (.0008 in)	67	52	43
.0015 (.0006 in)	71	55	46
.0010 (.0004 in)	75	60	51
.0005 (.0002 in)	83	67	58
.0002 (.0001 in)	89	74	65

after preliminary testing it is evident that thermal shifts and expansions were very large in magnitude compared to a low acceleration signal. Therefore, if dc response is provided it may be accurate only at moderate to high g levels.

Limitations concerning only the variable capacitance system deal with operating frequency and cable length. Tests demonstrated that increasing the operating frequency resulted in greater losses and smaller sensitivities. Higher frequencies also place more restrictions upon the length of the cable to obtain the correct portion of a wave length. The oscillator can be tuned with either a capacitor or an inductor depending upon the length of the cable. However, better results were obtained when the oscillator was tuned with an inductor and additional capacitors were avoided.

Limitations concerning only the eddy-current type of transducer involve the relationship between the operating frequency and the resonant frequency of the coil cable combination. This resonant frequency is the electrical frequency at which the coil-cable combination resonates. The cable can be represented approximately as a shunt capacitance and a series resistance connected to the coil as shown in the diagram.



To avoid very large temperature shifts, the operating frequency must be less than the resonant frequency. This means that the greater the cable capacitance, the lower the coil inductance must be for a given operating frequency. Lower coil inductance usually results in lower sensitivity. In addition, the cable resistance lowers the sensitivity, considerably in some cases, and increases the temperature shifts. Therefore, the cable provides limits to both the sensitivity and temperature compensation that can be achieved.

b. Coil Design Studies

The design of the coils for the eddy-current sensor involves many variables and boundary conditions. The following comments and results apply to the particular problem at hand and should not be construed to be of general applicability. In the following paragraphs, the main variables of interest are explained and their effect upon the design goals examined.

The target that the coils "look" at is, of course, the seismic mass described earlier. Its shape and dimensions are basically determined by the consideration of the 20,000 Hz frequency response design goal. Those considerations also determine the deflections the target will have. The target material will either be molybdenum or rhodium. Since these have similar resistivities ($6\mu\Omega\text{cm}$) one set of calculations can suffice for either material in the preliminary design. The target thickness was taken to be 0.279 cm (0.110 in) with a radius of 0.975 cm (0.384 in) from the 32,000 kHz natural frequency design. The coil outer radius is therefore bounded by the 0.975 cm dimension. Otherwise it would "see" the edge of the button, causing unpredictable effects. In the frequency range of interest, the target is effectively infinitely thick as far as the coil is concerned.

The coil's inner radius has a much smaller effect upon the inductance and the sensitivity of the coil than the outer radius. This remains correct as long as the inner radius is much smaller than the outer radius. We have decided upon an inner radius of 0.046 cm (0.018 in) based upon previous coil winding experience. If the inner radius is much smaller, it becomes more difficult to wind the coil uniformly. If the inner radius is much larger, the inductance decreases but the sensitivity also decreases in general.

As the coil's outer radius increases, the sensitivity increases provided all other parameters are held constant. The sensitivity is defined as the voltage out of the bridge for a given displacement. The larger radius coils (up to 0.975 cm have better sensitivity but, of course, also have higher inductance, and therefore lower natural frequencies. If the other dimensions are fixed, there is an optimum coil length. This optimum coil length, however, is affected by most of the other parameters involved in the coil design, and it is difficult to decide upon until most of the other parameters are fixed.

The size of the wire used to wind the coil has a variety of effects upon the characteristics of the coil. If the coil dimensions are fixed, a smaller wire will allow more turns to be wound upon the coil. Since the inductance is proportional to the square of the number of turns, the inductance increases rapidly. However, the smaller wire size increases the resistance of the coil very rapidly. These two effects combine in a very complicated fashion so that the sensitivity can be increased or decreased by smaller wire size depending on other parameters. The wire resistivity can also play a major role.

For the case at hand, there is an additional boundary condition in that because of the very long lead times to obtain coated wire, it was decided to use rhodium wire of 0.005 cm (0.002) O.D. coated with Secon "E" coating. The finished O.D. of the wire would be 0.010 cm (0.004 in). The other coil parameters were optimized using this type of wire. Preliminary studies indicate that no major improvements would be available with different wire sizes.

The sensitivity increases as the coil-to-target spacing (at zero acceleration) decreases. Therefore, the coil-to-target spacing will be as small as it can be reliably constructed.

The prototype coil designs offering the most promising properties consisted of the following parameter choices:

A. High-Frequency Coil

Operating Frequency:	5 MHz
Inner Radius:	0.046 cm (0.018 in)
Outer Radius:	0.203 cm (0.080 in)
Thickness:	0.010 cm (0.004 in)
Coil Wire:	Rhodium wire (0.005 cm O.D.) coated with Secon "E" coating. Coated wire size 0.010 cm.

B. Low-Frequency Coil

Operating Frequency:	1 MHz
Inner Radius:	0.046 cm (0.018 in)
Outer Radius:	0.279 (0.110 in)
Thickness:	0.030 (0.012 in)
Coil Wire:	Same as the high frequency coil

The calculated sensitivity of the high frequency coil will be approximately twice that of the low frequency coil; however, the lower frequency coil represents less of a departure from present Kaman technology.

SECTION VI

ACCELEROMETER DESIGN

After the completion of the analytical and experimental phases, a technical interim report was submitted to AFFDL/FBG. In the report, the accelerometer system using the capacitance plate design sensor with a variable-resonance (frequency-modulated) electronics was recommended. Such a recommendation was based on the fact that such a system offered the greatest advancements of technology and performance, despite the fact that more risks were involved. The recommendation was approved by AFFDL/FBG and the fabrication of the prototype sensor was begun.

1. Sensor Design

The sensor design is shown in Figure 13. The major design features of the sensor are the housing, expansion wedge, fixed capacitance plates, seismic diaphragm and the high temperature cable. The housing was designed to have no natural frequencies less than 40 KHz. The housing material was Haynes Alloy #8077 with the top cover fabricated from 309 stainless steel. Although the 309 stainless does not have the corrosion or oxidation resistance noted for the Haynes #8077 alloy, thicknesses of the various parts assure a useable lifetime of several hundreds of hours. The closure weld (sealing the 309 stainless part to the Haynes #8077 alloy) is a LASER weld of minimum penetration of 0.127 centimeters (0.050 inches).

The thermal expansion wedge was designed to maintain a tight fit of the internal stack of capacitance plate components through temperature excursions from ambient to 1093°C (2000°F). Both the alumina ceramic plates and the molybdenum seismic diaphragm are very low expanders.

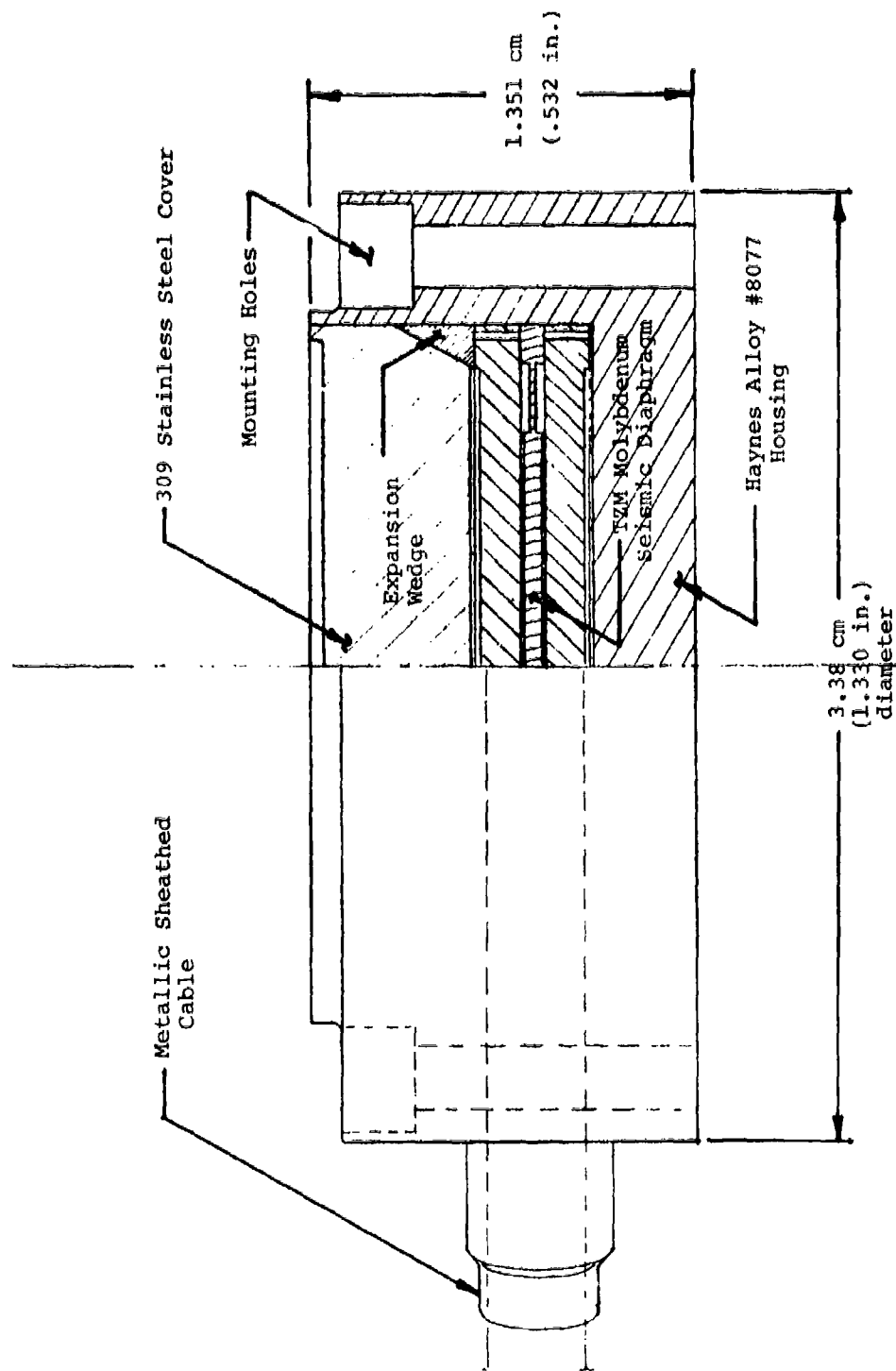


FIGURE 13. SENSOR CONFIGURATION

To compensate for this low expansion compared to the moderate expansion of the Haynes #8077 alloy, the higher expanding 309 stainless steel was selected to assure a "gap-free" assembly. When considering the 12.29 cubic centimeters (0.75 inches cubed) size goal of the sensor, a design was devised to shorten the length required to balance the expansion of the internal components and the external housing. This design called for the use of both the axial and radial expansion of the 309 stainless to be applied to the internal component stack through an expansion wedge. The maximum total axial expansion difference at 2000°F between the internal stack and the housing was 0.004 cm. (0.0016 in.). This additional expansion was provided through the conversion of the radial expansion through the 28 degree wedge shown. Precision fits and finely polished surfaces were used to provide part movement to allow the wedge design to operate properly.

The fixed capacitance plates were made of 94% purity alumina. The plates were lapped to precision flatness using diamond lapping compound. The ZGS platinum center conductor was then brazed to the ceramic on the capacitance plate side. The plate was again diamond lapped. The lapped surface was then flash vapor plated with platinum, followed by electroplating with rhodium to complete the unit.

The seismic diaphragm was constructed of TZM molybdenum. This particular grade of molybdenum contains 0.5% titanium and 0.8% zirconium and has a significant improvement of hot strength and recrystallization temperature over pure molybdenum. The hot strength at 1093°C is, of course, the main fact in its choice over platinum, rhodium or Haynes #8077 alloy as the seismic mass material. The most significant deficiency of this material is its reactivity with

oxygen and other elements at high temperatures. An inert gas backfill of 75% neon - 25% helium was used to eliminate any oxygen and a 0.0013 cm. (0.0050 in.) thick plasma sprayed alumina coating was used on the inside surfaces of the housing as a diffusion barrier to migration of nickel and other elements. Problems with diffusion into molybdenum, especially nickel, were noted in earlier chemical compatibility testing.

The high temperature cable consisted of Inconel Alloy 600 sheath, high purity alumina insulation and two ZGS platinum conductors. This cable is identical to that used for the 1093°C microphone system developed under Contract F33615-74-C-3011.

2. Electronics Design

Figure 14 shows the block diagram of the accelerometer electronics. It is a variable frequency system which uses differential techniques. There are two oscillators associated with the transducer. The frequency of a reference voltage controlled oscillator (VCO) is controlled by two inputs: the capacitance between one of the outer plates and the inner plate of the transducer and a frequency control input. The second oscillator is part of phase locked loop (PLL) #1. Its natural (or open loop) frequency is determined by the capacitance between the opposite outer plate and the center plate. However, since it is part of a PLL, its frequency will be forced to be the same as the reference VCO. The difference between the VCO frequency and the open loop PLL frequency is proportional to the acceleration signal. As can be seen, these two frequencies will move in opposite directions when the transducer is subject to an acceleration.

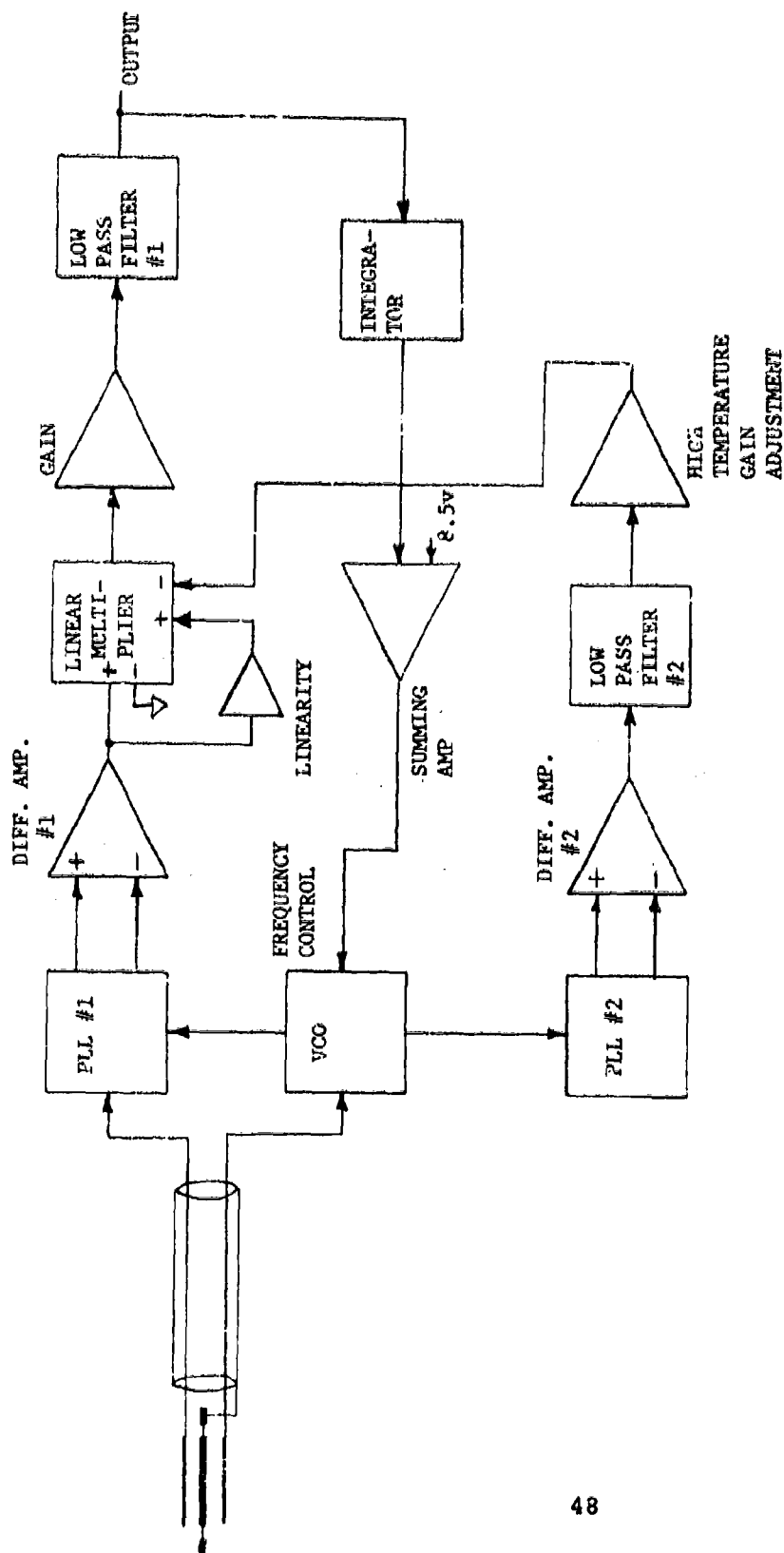


FIGURE 14. ELECTRONICS BLOCK DIAGRAM

This differential approach reduces the effects of cable capacitance change and temperature upon the acceleration signal zero and linearity.

The output of the PLL #1 is a differential signal, and differential amplifier #1 is used to convert the signal to a single-ended type. A special amplifier is used to handle a very high common mode voltage from the PLL. A linear multiplier follows the differential amplifier, and it serves two purposes. First, it provides a means to scale the output needed to correct for temperature sensitivity variations. Secondly, it provides a means to correct for small linearity variations by scaling the signal to a small degree by the signal itself. Following the multiplier is an adjustable gain amplifier and a low pass filter.

The information needed to correct for sensitivity variations is derived from PLL #2 and differential amplifier #2. This signal tells how far the oscillators have shifted due to temperature variations. This signal also has some acceleration signal present which is filtered with low pass filter #2. The signal is then scaled with the high temperature gain adjustment and then fed to the multiplier to scale the acceleration signal.

The frequency response of the system is limited on the low end to about 2 Hz. This is accomplished by integrating the acceleration signal output adding 8.5 volts and applying this to the frequency control input of the reference VCO. This forces the nominal frequency difference between the VCO and PLL #1 to be zero. This approach is used to reduce the possibility of the loop getting out of lock.

SECTION VII

ACCELEROMETER TESTING

The accelerometer was tested using the Unholtz-Dickie Model 350 vibration system. The transducer was attached to the shaker platform using a special water cooled fixture and was heated using a custom designed furnace. The furnace was capable of heating the sensor while being subjected to the vibration environment to temperatures near 1093°C.

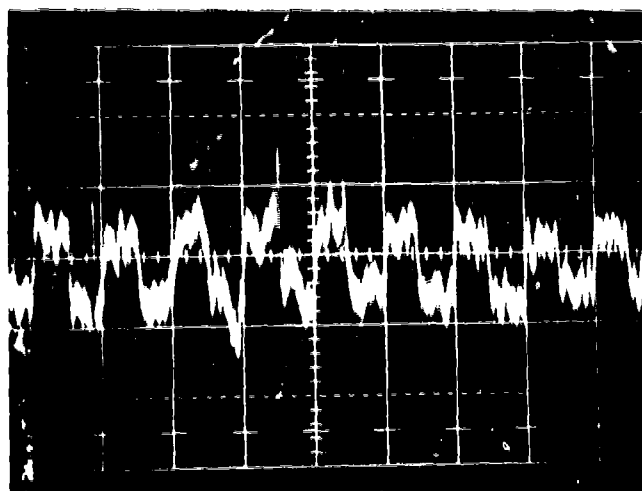
The first testing activities were conducted to examine possible fixture resonances that could cause errors in the observed accelerometer data. Several serious resonances were discovered at 3000 hertz and above, and thus all higher temperature data had to be observed at frequencies less than 3000 hertz.

During the first attempts to test the accelerometer, large zero shifts were associated with any change in temperature. Changes were made in the electronics to eliminate D.C. response, and testing was continued with the system as described in Section 6. The measurements were made using a standard wide-band root-mean-squared (rms) voltmeter and a tuned, or narrow-band rms voltmeter with the observed data listed in Table 3. Although in the final data run, no accelerations less than 0.05 g were measured, previous testing has shown the ability to measure 0.03 g or 90.5 dB. At 1010°C (1850°F) and 1066°C (1950°F), considerable noise started appearing on the output signals as shown in Figure 15. Until that point, clean, sinusoidal signals had been observed. It was thought that the expansion wedge described earlier was not working properly, and that gaps were present between the plates allowing movement. Capacitance measurements

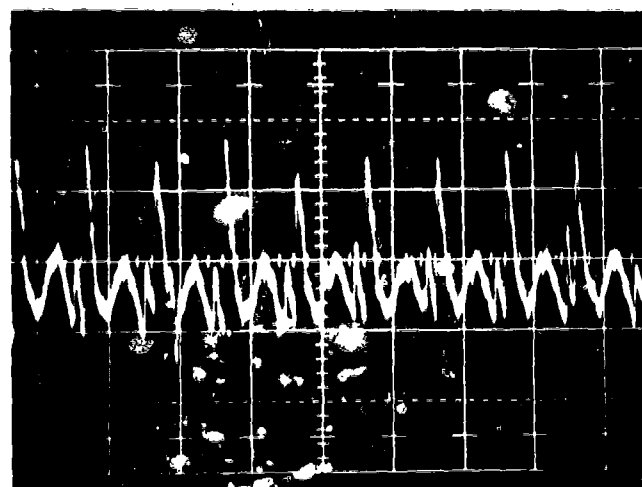
TABLE 3. TEST DATA

Temperature (°F)	Acceleration Level (g's)	Frequency (Hertz)	Output Signal (mv)	
			Broadband	Tuned
Ambient	.1	1000	.07	.063
"	1	1000	.65	.983
"	10	1000	9.68	9.983
1200	.05	1000	.04	.005
"	.1	1000	.08	.061
"	1	1000	.62	.973
"	10	1000	9.28	9.483
1600	.05	1000	--	.008
"	.1	1000	.06	.080
"	1	1000	.73	1.083
"	10	1000	12.28	12.488
1800	.1	1000	.02	.02
"	1	1000	5.78	5.788
"	10	1000	26.48*	24.988*
1950	1	1000	1.08*	1.388*
"	10	1000	3.98*	2.188*

* Signal showed excessive noise.



1g at 1000 Hertz
Vertical: 5mv/cm
Horizontal: 1 msec/cm



10g's at 1000 Hertz
Vertical: 10mv/cm
Horizontal: 1 msec/cm

FIGURE 15. ACCELERATION DATA AT 1066°C (1950°F)

at temperature under static conditions supported that hypothesis. After some effort to free the wedge by temperature cycling and shock loading, the sensor failed to operate at all. Careful examination of the sensor showed that the metal sheathed cable had partially failed at weld attachment to the sensor housing. With WPAFB/FBG approval, the sensor was then machined apart for failure analysis. The following conditions were observed after approximately 12 hours operation above 1010°C (1850°F) and 24 hours operation above 538°C (1000°F):

(1) Failure of the cable-to-sensor weldment had caused ZGS platinum lead wire failure and had allowed oxygen to enter into the interior of the sensor. Judging from the small amount of oxidation present on the TZM molybdenum seismic diaphragm, the precision fits of the internal assembly had not allowed the oxygen to penetrate the interior, this being substantiated by the notable oxidation of the Haynes alloy #8077 on the interior of the sensor near the weld failure.

(2) The TZM molybdenum seismic diaphragm was in good condition with only a slight surface oxidation noticeable. Efforts to clean off this coating were successful. No attempts to evaluate nickel diffusion were made, but the plasma sprayed alumina was in excellent condition and very white in color, indicating that it had been successful as a diffusion barrier to any diffusion of metallic species. Any diffusion would have changed the color to shades varying from gray to black.

(3) The rhodium plated capacitance plates were in excellent condition. Surface resistance had not changed, and there was no indication of the plating delaminating from the alumina substrate.

(4) The expansion wedge was not free to move and had apparently diffusion bonded itself to the cover. In this condition, where no differential movement was possible, the capacitance plate stack would become loose at higher temperatures. This condition would explain the noisy signals observed at 1010°C and above.

(5) The closure weld of the cover to the housing was in excellent condition. In excess of 0.152 cm (0.060 in.) penetration was observed. The oxidation of the 309 stainless steel was not excessive and had not degraded the weldment at all.

1. Performance Comparison With Design Goals

Although limited testing experience was obtained, the accelerometer system showed great promise and was successful in many ways. With regard to the top four priorities, the sensor performed as follows:

- (1) Operation at 1093°C - Goal met. Operated at high temperature for approximately 12 hours.
- (2) Frequency Range 2 to 20,000 hertz - Engineering decision to design system with only 2 to 7,000 hertz range.
- (3) Dynamic range .01 to 1000 g's (100 dB) - Observed a minimum of 0.02 g's (91 db).
- (4) Temperature range sensitivity shift of $\pm .5\%$ - Observed $\pm 10.46\%$ from ambient to 871°C (1600°F) at 0.1 to 10 g's.

A complete list of each design goal and actual performance is presented in Table 4.

TABLE 4. DESIGN GOAL AND PERFORMANCE COMPARISON

<u>Design Goal</u>	<u>Performance</u>	<u>Remarks</u>
1. Operating Temperature Range: -54 to 1093°C (-65 to 2000°F)	Tested to 1066°C (1950°F)	Limited by special furnace design
2. Frequency Response: 2 to 20,000 Hertz	Designed for useable range of 2 to 7000 Hertz	Design choice to have resonant frequency at 10,000 Hertz
3. Dynamic Range: 100 dB (0.01 g to 1000 g)	Measured 91 dB	
4. Sensitivity: Vary no more than +.5% over given temperature range.	Approximately +10% ambient to 871°C (1600°F)	Sensor failed before system could be optimized
5. Linearity: Within +.1% over entire dynamic range	Approximately +20% ambient to 871°C (1600°F)	Same as above
6. Resonant Frequency: 32,000 Hertz or above	Housing resonant frequency at 32 kHz	No means for testing

TABLE 4. (Continued)

<u>Design Goal</u>	<u>Performance</u>	<u>Remarks</u>
7. Cross-axis Sensitivity: Less than 1%	Unknown	Not tested
8. Acoustic Noise Sensitivity Less than .01g equivalent at 140 dB SPL (Ref. to 2×10^{-4} microbar)	Unknown	Not tested
9. Static Stability: 0.1% at a given temperature over extended periods of time	Unknown	Not tested
10. Dynamic Stability: Less than 10 dB shift above noise floor from temperature transients of up to 2.78°C (5°F)/second over the given temperature range.	Unknown	Not tested
11. Size: 12.29 cm^3 (.75 in ³) or less	12.12 cm^3 (.740 in ³)	Design goal met
12. External Electronics: If required shall be simple, low power, compact and flight qualified	Simple, low power, small size (385 cm^3 (23.5 in ³))	Not tested for flight qualification Size goal met

SECTION VIII

CONCLUSION

Although not all the objectives and design goals of the program were met, many significant advancements in high temperature materials and techniques and electronics design were made. The activities of this development resulted in the extension and advancement of the 1093°C (2000°F) materials technology to the design of an accelerometer system utilizing variable capacitance techniques. The fabricated sensor utilized many materials from previous development programs, but saw the extension of technology include the use of metallized ceramics and refractory metals. The development of the variable resonance electronics was also an advancement of state-of-the-art high signal-to-noise electronics.

Many of the design goals were achieved to a high degree or as planned, including operation to 1093°C (2000°F), frequency response, dynamic range, resonant frequency, sensor size, and external electronics design. Other goals involving output or response characteristics were not fully characterized because of the premature failure of the sensor. Activities resulting from the failure analysis also indicated that no serious technological problems existed which could not be corrected with simple design changes.

Finally, it is felt that the development effort was a valuable experience, and the resulting technology will provide future efforts with sufficient background to develop satisfactory acceleration measuring systems. Such systems will provide AFFDL/FBG the capability to keep pace with the measurement needs created by the technological advancements in the field of high speed flight.

SECTION IX

RECOMMENDATIONS

It is the recommendation of the authors of this report that additional research effort be conducted to complete the development of the capacitive accelerometer system. Since the transducer described in this report has most of the important characteristics of acceptable temperature range, dynamic range, frequency response, size and electronics, it is felt to be in the best interest of the Air Force to continue this effort to fully characterize the accelerometer system. The efforts of a continued program should include:

(1) Sensor design changes noted in the failure analysis which would include (a) the use of other case materials to eliminate the use of the expansion wedge and (b) a more rigid attachment of the instrumentation cable to the sensor housing. Rolled Alloys R-333 would be such a material that would be suitable for the environment and would not represent a departure from the present materials technology. The cable attachment and perhaps sheath thickness should be reviewed carefully to avoid premature cable failure.

(2) Electronics evaluation and review for sensitivity and linearity adjustments. The sensitivity adjustment still needs a more suitable means of compensating for capacitance changes associated with the large temperature excursions. Although the present system does work, total evaluation was not possible since the signal at very high temperature became quite noisy, probably due to the expansion wedge problem.

Signal linearity adjustment also needs more evaluation. Again, the limited performance at the high temperature extreme did not make it possible to fully evaluate this adjustment.

In addition to these efforts, additional testing with tuned bridge electronics is suggested as an option. With such electronics, Kaman has achieved 100 dB dynamic range, and the temperature compensation techniques are readily understood. Kaman uses such electronics with their many high temperature products.



DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 88TH AIR BASE WING (AFMC)
WRIGHT-PATTERSON AIR FORCE BASE OHIO

MEMORANDUM FOR: DTIC - OQ

21 September 2004

Attn: Larry Downing
8725 John J. Kingman Rd.
Ft. Belvoir VA 22060

FROM: 88 CG/SCCM (FOIA Office)
Bldg 1455
3810 Communications Blvd
WPAFB OH 45433

SUBJECT: Freedom of Information Act (FOIA) Case, WPAFB FOIA Control # 04-516AB

1. On 07 September 2004, we received a FOIA request for document AD-B017355 "Development of a 1093 C (2000 F) Prototype Accelerometer". The current distribution statement B (unclassified/limited) is no longer applicable. The document has been reviewed by The Air Force Research Lab Air Vehicles Directorate, and it has been determined that the distribution statement should be changed to statement A (publicly releasable).

2. I am the point of contact and I can be reached at (937) 522-3092 or DSN 672-3092.

A handwritten signature in black ink, appearing to read "Abby L. Boggs", is located below the second point of the memorandum.

ABBY L. BOGGS
Freedom of Information Act Analyst
Management Services Branch
Base Information Management Division

Attachment
AFMC Form 559